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EDITORIAL

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A century of national forest inventories – informing past, present and future decisions

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Abstract

In 2019, 100 years had elapsed since the first National Forest Inventory (NFI) was established in Norway. Motivated by a fear of over-exploitation of timber resources, NFIs today enable informed policy making by providing data vital to decision support at international, national, regional, and local scales. This Collection of articles celebrates the 100th anniversary of NFIs with a description of past, present, and future research aiming at improving the monitoring of forest and other terrestrial ecosystems.

Introduction

The establishment of the Norwegian National Forest Inventory (NFI) in 1919 was motivated by a fear of over-exploitation of timber resources. Just a few years later – in the 1920's – similar monitoring programs were to follow in Finland, Sweden and the USA (Tomppo et al. 2010). In the 1960's, during the World War II reconstruction phase, the NFIs of France, Austria, Spain, Portugal and Greece, were initiated (Vidal et al. 2016). Concerns regarding acid rain in the 1980's were a trigger for initiating NFIs in central Europe. In recent years, climate change (REDD+) has prompted the establishment of new NFIs, especially in developing countries, while most developed countries now have regular NFI programs.

One hundred years ago, the primary motivations for establishing NFIs were to obtain an overview of timber resources and to guide the sustainable use of the forest resources. Since then, NFIs have gradually evolved to provide answers for a much broader range of issues. While monitoring timber resources and sustainability is still a major component, NFIs today also monitor forest damage and diseases, forestry management, carbon

sequestration as well as biodiversity indicators and many other ecosystem services in general. Today, NFIs enable informed policy making by providing data vital to decision support at international, national, regional and even local scales. For example, NFIs provide data to international reporting under the United Nations Framework Convention on Climate Change, and to international forest health monitoring programs. In line with the widening of objectives during the past century, techniques and sampling designs in NFIs have evolved to provide relevant answers for societal problems.

From May 19th to 23rd 2019 the Norwegian NFI team took the opportunity to celebrate the first 100 years of NFI history by bringing together researchers and practitioners with an interest in forest monitoring in Sundvollen, Norway. Approximately 200 participants from more than 20 countries discussed past challenges, lessons learned, and methods for improving future large-scale forest and landscape inventory programs via more than 100 presentations and posters. Exhibitors presented their measurement devices and services in the poster hall, and during a field excursion the five Nordic NFIs explained their plot setups in the forest. Six keynote speakers gave far-sighted presentations that introduced session topics and were live-streamed for those who could not participate in person.

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While the program and abstracts of the conference are available at NIBIO (2019), this Collection (special issue) combines multiple scientific articles of which most were presented at the conference (Fig. 1). A total of 14 papers passed the review process coordinated by the Guest Editors who are the authors of this Editorial. We are grateful for 58 expert reviewers who ensured high scientific quality. The published articles can be categorized into three topics: i) descriptions of NFI programs and their histories, ii) new estimators and methods including the use of remotely sensed data, and iii) use of NFI data for greenhouse-gas reporting and monitoring ecosystem services.

The challenges of the currently on-going Corona pandemic imposed on societies in general affect NFI programs as well. Travel restrictions within and between countries reduce the availability of qualified field workers, and training courses essential to calibrate field assessments are difficult to conduct. Even though these challenges have developed after publication of most papers in this Collection, we expect that the Collection will provide relevant information for ongoing and future forest monitoring programs.

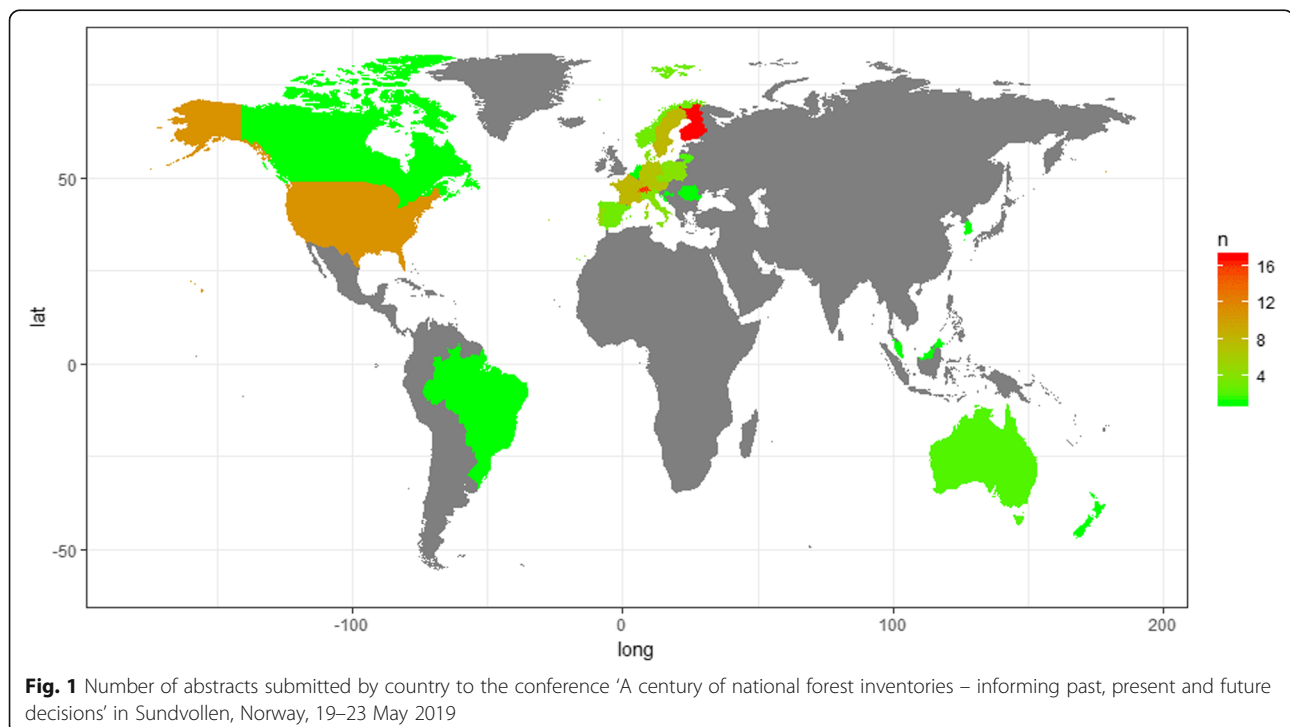
NFI programs and their history

This Collection contains descriptions of the first NFI which was conducted in Norway (Breidenbach et al. 2020) and two new members of the NFI family, namely the Bangladesh Forest Inventory (Henry et al. 2021) and

the Natural Forests Inventory of New Zealand (Paul et al. 2021).

Breidenbach et al. (2020) describe the development of the Norwegian NFI since 1919 and how present challenges likely will influence future developments. The Norwegian NFI started as a line-based transect survey and today uses more than 22,000 permanent sample plots to survey land-use and land-use change, primarily based on remotely sensed data. More than half of the sample plots are located in 12 Mha of forest and facilitate monitoring of more than 100 variables. The development of the Norwegian Forest Resource Map, *SR16*, which is based on a combination of NFI field plots, airborne laser scanning, image matching, and satellite data, addresses the current increasing demand of policy makers and other stakeholders for forest information in the form of fine resolution maps. Forest resource maps can, however, also be used to improve estimates of population parameters which is of special interest for small areas in NFIs (Breidenbach et al. 2020).

Henry et al. (2021) document methods for designing and conducting the NFI of Bangladesh which was implemented 2016–2019. It is designed as a permanent program and consists of a resource and socio-economic survey. Information is obtained from a combination of more than 1700 field plots with remotely sensed data and interviews of 6400 households. The full development of the inventory, from the creation of a land-use map to the optimization of the sampling design and governance measures ensuring a continuous commitment to forest monitoring, is described (Henry et al. 2021).



Paul et al. (2021) present methods for estimating carbon stocks and stock changes in New Zealand's pre-1990 natural forests using field measurements from two inventory cycles. Estimates of above-ground biomass used individual tree measurements, although a small proportion of the plots was measured only at the first time point and a regression model was constructed to predict the carbon stocks of those plots at the second time point. The estimates show that New Zealand's natural forests are in carbon balance; they are neither a carbon sink nor a carbon source.

New estimators and methods

NFIs are typically based on approximate systematic grids of sample plots which generally produce conservative (i.e., too large) estimates of uncertainty if design-based estimators assuming simple random sampling (SRS) are used. Magnussen et al. (2020) document the 100-year long quest of improving variance estimation in systematic sampling using model-based methods and add previously untested estimators to the set of alternatives to using simple expansion estimators with SRS. Of importance for NFIs, they conclude "In large populations, and a low sampling intensity, the performance of the investigated estimators becomes more similar" (Magnussen et al. 2020).

The local pivotal method (LPM) is a form of balanced sampling method that produces small uncertainties with a minimum number of sample plots which, of course, is of considerable relevance for NFI programs. In the context of the Finnish NFI, Rätty et al. (2020) found, however, that LPM-sampling could not markedly improve estimates based on systematic sampling when considering several variables of interest as is typical in NFIs. Complementing the study by Magnussen et al. (2020), Rätty et al. (2020) identify a variance estimator originally developed for LPM that is well-suited for systematic sampling.

In a simulation study, Kangas et al. (2020) show that old measurements on permanent sample plots can constitute valuable source of auxiliary information for augmenting and complementing high-quality airborne laser scanning (ALS) data. The study highlights data-fusion opportunities with model-assisted and model-based estimators.

The hierarchical model based approach (HMB) is a method for propagating uncertainties from multiple regression models when combining multiple remotely sensed data layers. Saarela et al. (2020) advanced an analytical HMB method for the important class of non-linear models. In an ALS-based application, they show the close connection between fine resolution mapping and model-based inference for estimators for areas that aggregate arbitrary numbers of mapped pixels. At the

scale of their study area, the use of HMB revealed that 75% of the uncertainty in biomass estimates was caused by uncertainties in tree-level biomass model parameter estimates.

Kleinn et al. (2020) describe how a new perspective on continuous landscape variables, such as full-tree biomass, can reduce uncertainty in estimates using common field sampling. With their *continuous approach*, the spatial, 2-dimensional biomass distribution of trees is modelled, instead of aggregating all biomass to the point of the stem position as with the traditional approach. The surface that is surveyed using sample plots is smoother in the continuous approach relative to the traditional approach and, thereby, reduces the sample variance. New measurement methods such as terrestrial laser scanning (TLS) make the continuous approach an interesting option.

The age of forest stands is critical information for forest management and decision-making. However, this information is usually not available at fine resolution for large geographic scales. Two studies in this Collection describe the development of regression models for large-area mapping of forest age using a combination of NFI, ALS, and other data (Maltamo et al. 2020; Schumacher et al. 2020). Using Norwegian NFI data, Schumacher et al. (2020) model stand age by exploiting tree height predicted from ALS, a site index prediction map, and Sentinel-2 data as predictor variables. Satisfactory results were obtained, especially for stands with large site indices. Using Finnish NFI data, Maltamo et al. (2020) exploit ALS and geographical data to model stand age. They highlight that the utility of age predictions varies according to applications. In contrast to Schumacher et al. (2020), Maltamo et al. (2020) focus on managed forests younger than 100 years of age.

Greenhouse-gas reporting and monitoring ecosystem services

The current importance of information on carbon stock changes and ecosystem services is underlined by four studies based on the Swiss NFI.

Traub and Wüest (2020) analyze the quality field data of the woody species composition and provide several approaches for doing so. They find that data quality was as great as 30% less than the expected data quality limit, and the percentage of omitted species was as great as 20% less. These results show the relevance of considering information on NFI data quality in terms of the reproducibility of collected data.

Hararuk et al. (2020) developed deadwood decay models from repeated Swiss NFI measurements which show-cases the contribution of long-term NFI monitoring programs to understanding deadwood dynamics. The inclusion of decay drivers allows the application of

the models in carbon budget simulations that integrate above-ground and soil carbon pools.

Temperli et al. (2020) study the trade-offs between ecosystem service provision and the predisposition to disturbances using the Swiss NFI for five different scenarios: a business-as-usual (BAU) scenario and four scenarios with increased timber harvesting. The results were evaluated using indicators for forest ecosystem services and biodiversity, including timber provision and predisposition to disturbances. Increased timber production without increasing the proportion of conifers generally reduced predisposition to disturbances but was in a trade-off with biodiversity indicators.

Didion (2020) describes a method for obtaining comprehensive and consistent estimates of herb layer biomass on NFI plots to complement biomass estimates for the tree and tall shrub layer. The estimates are based on a model requiring elevation and vegetation cover as predictor variables.

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Authors' contributions

J.B. wrote the first draft to which all authors contributed. The authors read and approved the final manuscript.

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Declarations

Ethics approval and consent to participate

Not applicable.

Consent for publication

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Competing interests

We declare no competing interests.

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